STABILITY AND PHASE NOISE TESTS OF TWO CRYO-COOLED SAPPHIRE OSCILLATORS*

G. John Dick and Rabi T. Wang

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109

Abstract

A cryocooled Compensated Sapphire Oscillator (CSO), developed for the Cassini Ka-band Radio Science experiment, and operating in the 7K - 10K temperature range was previously demonstrated to show ultra-high stability of $\sigma_y = 2.5 \times 10^{-15}$ for measuring times 200 seconds $\leq \tau \leq$ 600 seconds using a hydrogen maser as reference [1]. CSO-1 and CSO-3 are now both operational with new low noise receivers. We have made initial phase noise and Allan Deviation measurements that show more than ten times stability improvement over the hydrogen maser for measuring times 1 second $\leq \tau \leq$ 10 seconds, and indicate performance for the individual units of $\sigma_y \approx 3 \times 10^{-15}$ for measuring times from 10 to 1000 seconds. Phase noise is reduced by 20 to 28 dB over the design offset frequency range from 1 Hz to 40 Hz. Receiver design is also discussed.

1   Background

Cryogenic oscillators operating below about 10K offer the highest possible short term stability of any frequency sources. However, their use has so far been restricted to research environments due to the limited operating periods associated with liquid helium consumption. The cryocooled CSO is being built in support of the Cassini Ka-band Radio Science experiment and is designed to operate continuously for periods of a year or more. Performance targets are a stability of $3\text{-}4 \times 10^{-15}$ (1 second $\leq \tau \leq$ 100 seconds) and phase noise of -73dB/Hz @ 1Hz measured at 34 GHz. Installation in 5 stations of NASA's deep space network (DSN) is planned in the years 2000 - 2002.

In the previous tests, actual stability of the CSO for measuring times $\tau \leq$ 200 seconds could not be directly measured, being masked by short-term fluctuations of the H-maser reference. Excellent short-term performance, however, could be inferred by the success of an application of the CSO as local oscillator (L.O.) to the JPL LITS passive atomic standard, where medium-term stability showed no degradation due to L.O. instabilities at a level of $\sigma_y = 3 \times 10^{-14}/\tau$. A second and third CSO have now been constructed, and all cryogenic aspects have been verified, including resonator turn-over temperatures of 7.907 K and 7.336K. Q's for both resonators are greater than 10^9. These values compare to a turn-over of 8.821 K and Q of 1.0×10^9 for the first resonator. Operation of this second unit provides a capability to directly verify for the first time the short-term (1 second $\leq \tau \leq$ 200 seconds) stability and the phase noise of the CSO units.

The RF receiver used in earlier tests was sufficient to meet Cassini requirements for $\tau \leq$ 10 seconds but had short-term stability limited to $\approx 4 \times 10^{-14}$ at $\tau = 1$ second, a value 10 times too high to meet our requirements. A new low-noise receiver has been designed with noise performance of $\approx 10^{-15}$ performance at 1 second. Short-term performance was degraded in the old receiver due to insufficient tuning bandwidth in a 100MHz quartz VCO that was frequency-locked to the cryogenic sapphire resonator. The new receivers are designed for sufficient bandwidth, loop gain and low noise to achieve the required performance.

2   Design Aspects

The mechanical support system for the cryocooler and dewar are shown in Fig. 1. The interpenetrating box design allows both Dewar and cryocooler supports to be very rigid, with mechanical resonances external to the dewar itself above 70 Hz. A principal point of contact is the helium-confining fiber-reinforced bellows between them. To reduce such coupled vibrations, the cryocooler is mounted as rigidly as possible to the floor. The dewar's box is supported by 8 commercial vibration isolators as can be seen in the figure.

Our experience to date indicates that this mounting system is successful at virtually eliminating vibration-

Figure 2: Schematic diagram of the "low noise" CSO receiver. An inner, phase locked, loop effects an offset of the X-band VCO frequency from the 13th harmonic of the 800 MHz primary VCO at 10.400 GHz to match the actual sapphire resonator frequency. In this way the (slower) Pound frequency lock circuit keeps the 800 MHz VCO operating "on frequency".

Figure 1: Interpenetrating boxes provide independent rigid mounting structures for the cryocooler and Dewar with mechanical resonant frequencies above 50 Hz. The cryocooler support structure is rigidly attached to the cement floor while the dewar is supported on shock-absorbing mounts.

induced phase noise fluctuations below about 40 Hz. The small remaining fluctuations in this low frequency range appear to be due to helium gas expansion and contraction as the temperature of the cold head fluctuates each cycle. Vibrations above about 40 Hz are significant, limiting the excellent phase noise performance to lower frequencies.

The new "low noise" receiver is shown in Fig. 2. We find that stable operation of the outer "Pound" frequency lock loop requires a very tight inner loop. This in turn restricts the offset frequency in the inner loop to values above about 4 MHz. At lower offset frequencies, the outer loop becomes unstable at the gains desired.

We have ordered sapphire resonators with size constraints that give various frequencies centered on 10.400 GHz. All of the resonators are within 20 MHz as we had designed with most within about 6 very close to MHz. However, one is very close to 10.400 exactly, and will need to be reground to bring it at least 4 MHz away.

The preferred output frequency is 800 MHz, with performance difficult to verify at 100 MHz. All frequency stability comparisons reported here were done by differencing two 800 MHz signals.

3   Experimental

The temperature turn-over for CSO-3 is shown in Fig. 3. The actual value is a little lower than we had originally designed for, but cryocooler and dewar performance have been excellent, and weak spin-coupling
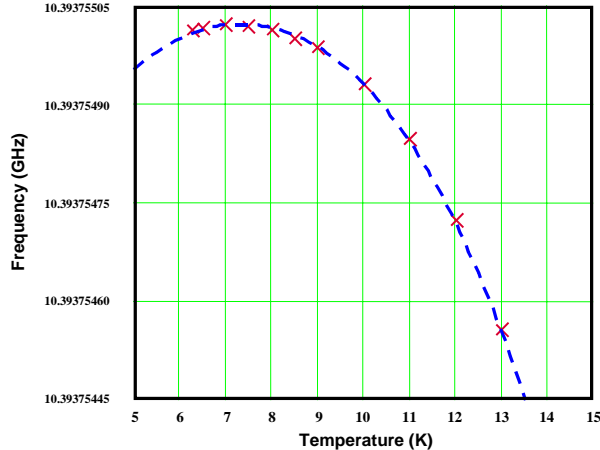
Figure 3: Temperature turnover characteristics for the CSO-3 resonator showing a curve fit with an extremum at 7.38 K. Turnover temperatures of the first two resonators were previously reported as 8.34 K and 7.907 K.
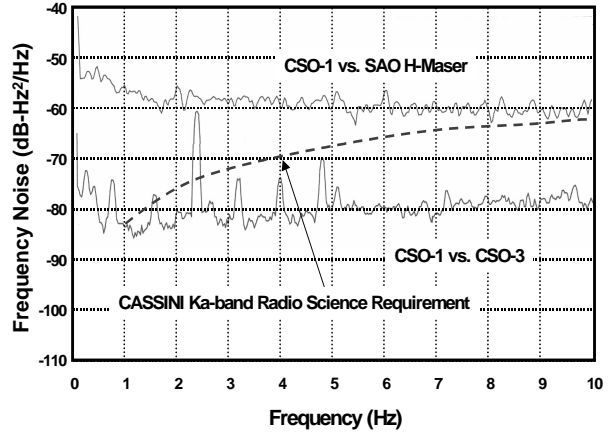

Figure 4: Measured frequency noise at 10.4 cavity frequency. One CSO was used as a frequency discriminator to make each of these measurements. Input frequency to the discriminator setup was 100 MHz for the Maser measurement and 800 MHz for the double CSO test. The CASSINI requirement corresponds to $S_\phi = -83$ dB/Hz at 10.4 GHz.

and low temperature both impact resonator Q. The resonator for CSO-3 is somewhat overcoupled, but still shows a loaded Q above 6×10^8.

CSO-1 and CSO-3 are now both operational with low-noise receivers installed. We have made initial phase noise and Allan Deviation measurements that validate our performance estimates.

Pair stability measurements show an Allan Deviation of 1.0×10^{-14} at 1 second and 5×10^{-15} at 10 seconds. Assuming both units are similar their individual performances are 7×10^{-15} at 1 second and 3.5×10^{-15} at 10 seconds. These results are approximately 10 times better than the hydrogen maser in this time range.

Pair stability measurements show an Allan Deviation of 1.3×10^{-14} at 1 second and $\approx 4 \times 10^{-15}$ for measuring times between 10 and 100 seconds. Assuming both units are similar their individual performances are 8×10^{-15} at 1 second and $\approx 2.5 \times 10^{-15}$ for 10 to 100 seconds. These results are approximately 10 times better than the hydrogen maser in this time range. phase noise measurements show a corresponding 20 to 28 db improvement over the best of the masers in the frequency range 1Hz to 40Hz. These tests verify that the noise performance of the CSO's meet the Cassini Ka-band requirement of -73dBc/Hz (referenced to Ka-band) all the way down to 1 Hz.

Phase noise measurements show a corresponding 24 to 28 db improvement over the best of the masers in the frequency range 1Hz to 40Hz. These tests verify that the noise performance of the CSO's meet the Cassini Ka-band requirement of -73dBc/Hz (referenced to Ka-band) all the way down to 1 Hz.

A small spectral bright line shows in these initial tests at the cryo-cooler cycle frequency of 2.4 Hz This small line could not be seen in previous tests, being masked by maser noise, and we expect to eliminate it with further optimization of the mechanical configuration. Based on our past experience it is likely due to helium pressure fluctuations, especially since the helium vents constructed for this purpose were not in use. Further improvement in the 1 second Allan Deviation is also expected.

4 Conclusions

The first tests of a pair of long-running cryocooled ultra-high stability short-term frequency standards demonstrated the short-term stability and low phase noise hoped for.

The 10K Compensated Sapphire Oscillator continues as the first continuously operable frequency standard with ultra–high short term stability. The first unit is expected to be installed at DSS-25 at NASA's Goldstone antenna complex in California in early '00. Passive atomic standards such as the LITS and Cesium Fountain can be operated continuously while realizing their inherent capabilities.

References

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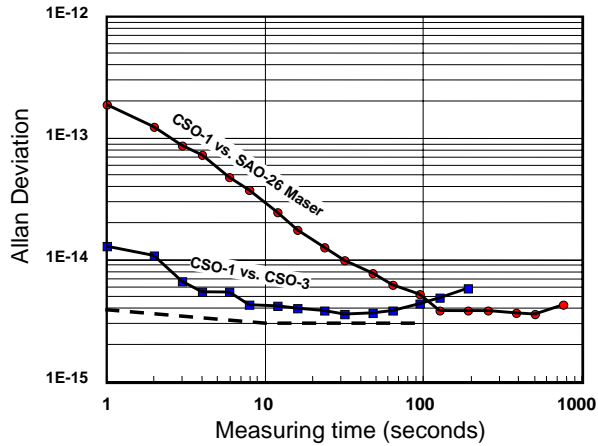
Figure 5: Preliminary stability measurements for two CSO units with the new receivers. Short term stability is much higher than for the hydrogen maser reference, and, on a per unit basis, is below 1×10^{-14} for all measuring times between 1 and 1000 seconds. The CASSINI requirement for a single unit is shown by the dashed line.

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